Breakdown Degradation Associated With Elementary Screw Dislocations in 4H-SiC p^+n Junction Rectifiers

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Micropipe Defects in SiC
(Review)

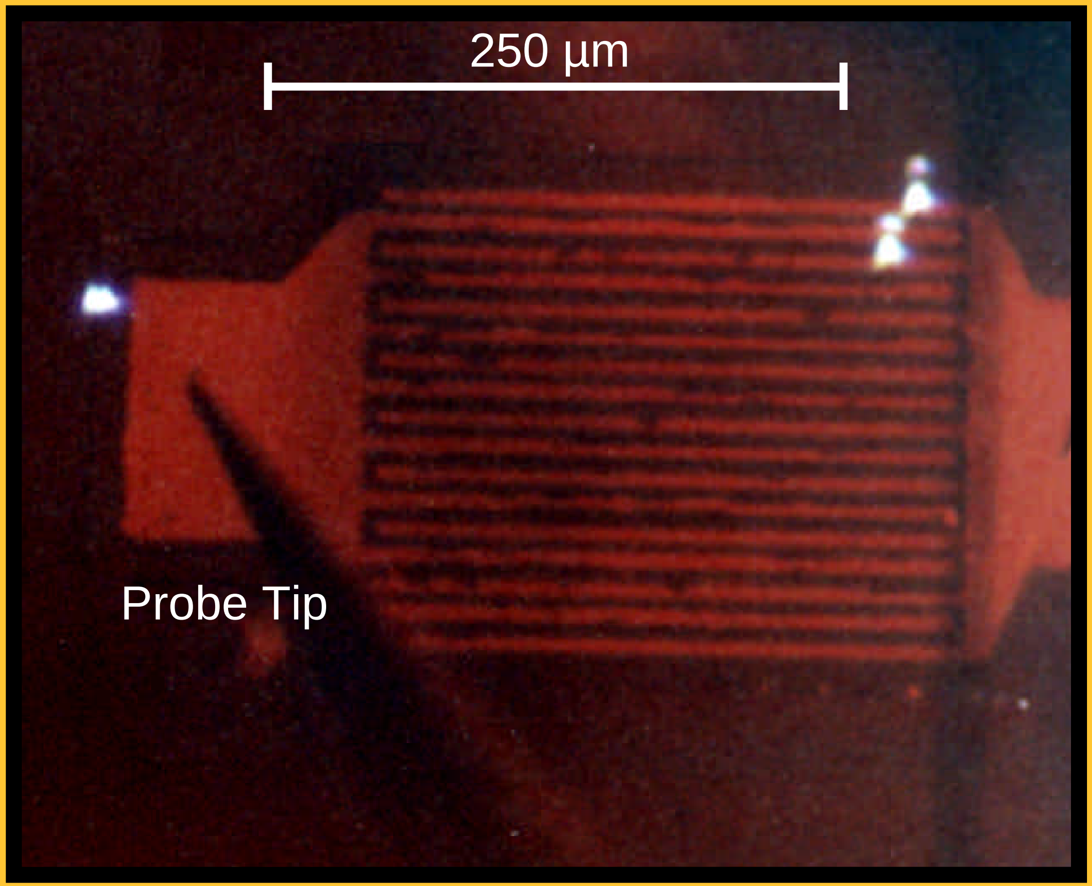
Micropipe defects present in SiC prevent scale-up of excellent small-area SiC prototypes into useful large-area high-current (> 10A) power devices.

- Present in commercial c-axis PVT wafers (30 - 200 / cm^2).
- Hollow-core screw dislocations (multiple Burgers vectors > 1c).
- Propagate into epilayers (non-terminating nature of screw dislocations).
- Cause localized junction failure well below SiC breakdown field.

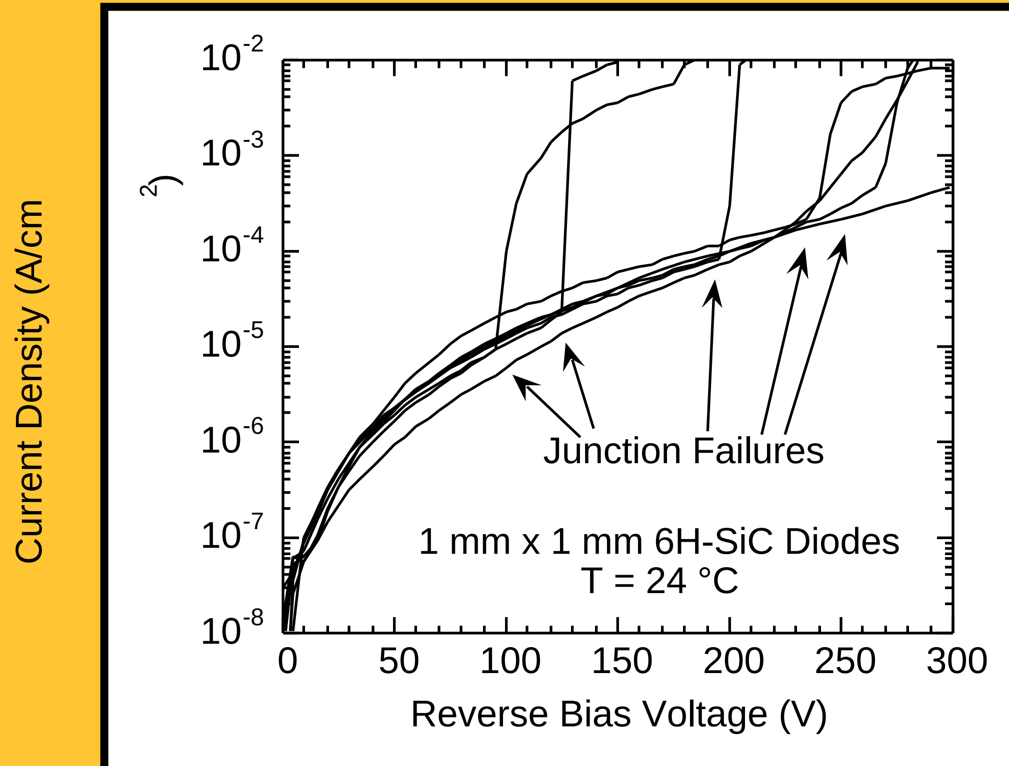
Steady progress in micropipe reduction.

- “Best Wafer” densities reduced from ~100 in 1993 to ~1 in 1997.
- DC prototype single-device currents up from ~0.5 A in 1993 to ~10A in 1997.

Micropipe Failure Microplasmas in 6H-SiC Transistor



Micropipe Reverse-Bias Failure Characteristics (pn Junction)



Diodes without micropipes block ~1000 V.

P. G. Neudeck, J. A. Powell, IEEE Electron Dev. Lett., vol. 15, no. 2, p.63 (1994).

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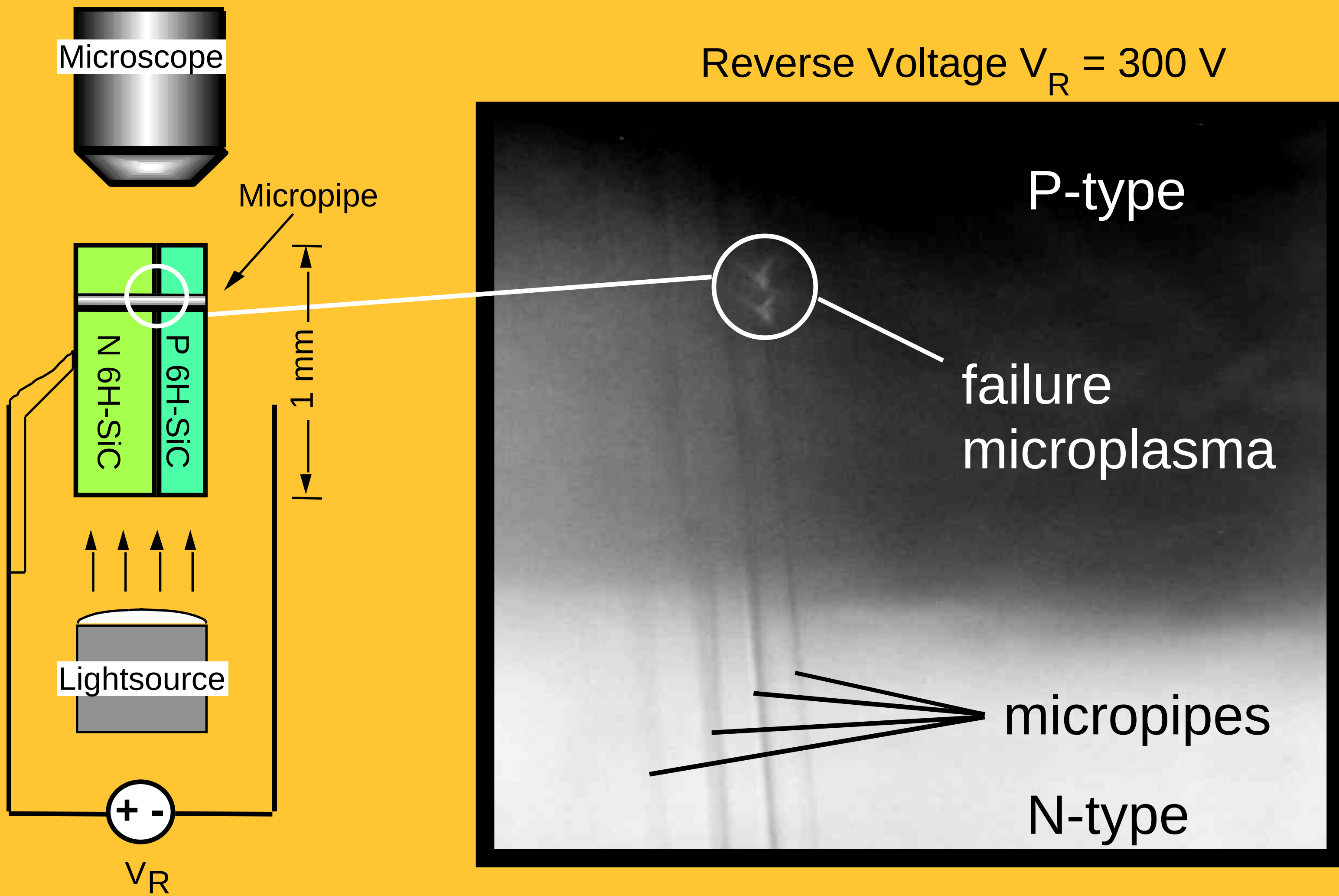
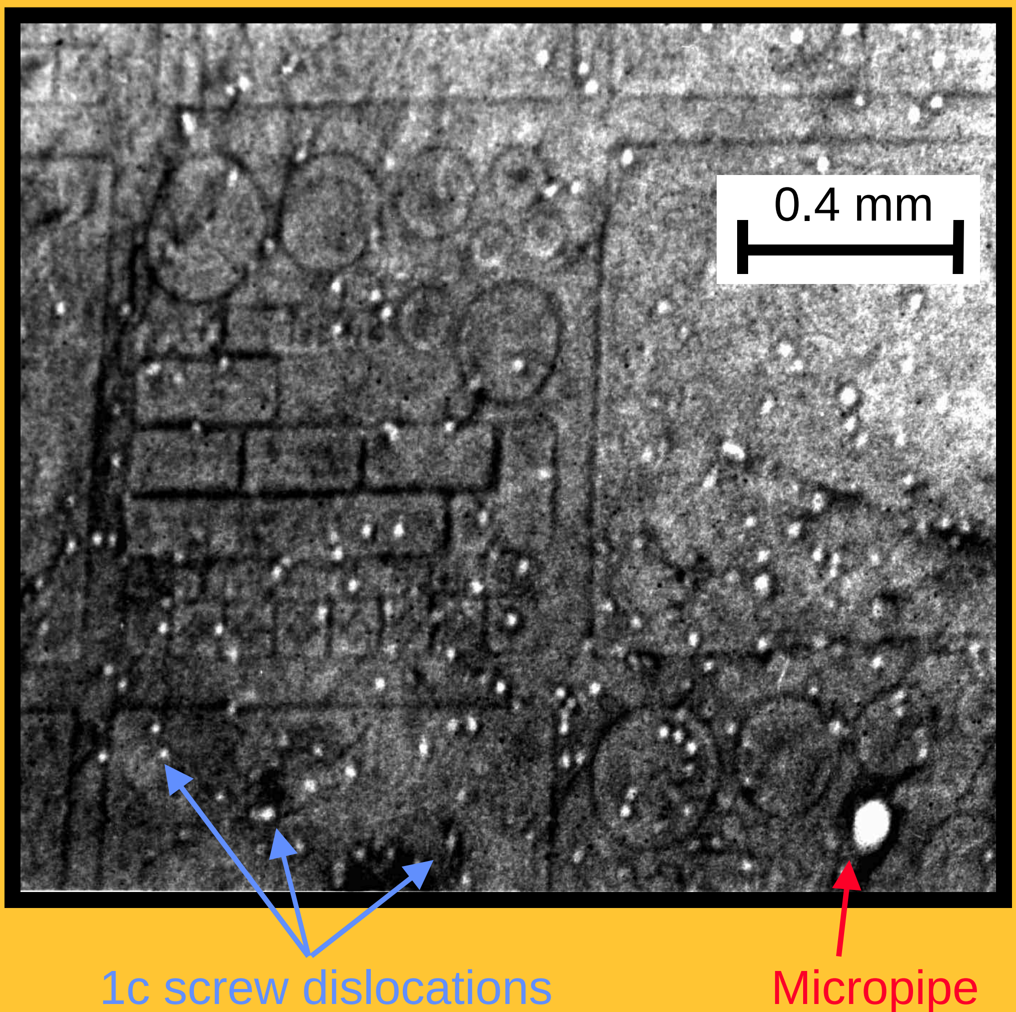
PN Junction Failure at Micropipe



Non-Micropipe Defects in SiC Wafers

X-Ray Topographic Image of
4H-SiC Wafer Section



Elementary Screw Dislocations

- Observable by Synchrotron White Beam X-Ray Topography (SWBXT).
- Non-hollow (closed) core.
- Screw Dislocations of Burgers vector = 1c.
- Densities of 3000 - 15000 / cm^2 in commercial SiC wafers (~ 100 X micropipe densities).
- Propagate into epilayers.
- Not as detrimental to electrical device characteristics as micropipes.

Low-light optical micrograph of 0.9 x 0.9 mm 4H-SiC p^+n diode biased in reverse breakdown (probing p^+ cap layer with no contact metal)

Device with no micropipes.

Nonuniform breakdown.

"Constellation" of reproducible breakdown microplasmas.

Microplasma density consistent with known elementary screw dislocation densities.

Experimental Approach

Fabricate epitaxial 4H-SiC p^+n junction diodes, compare electrical characteristics of diodes with and without defects.

Fabricate devices of varying areas (from 7×10^{-6} cm^2 to 1×10^{-2} cm^2).

- Many smaller-area devices free of certain kinds of defects.

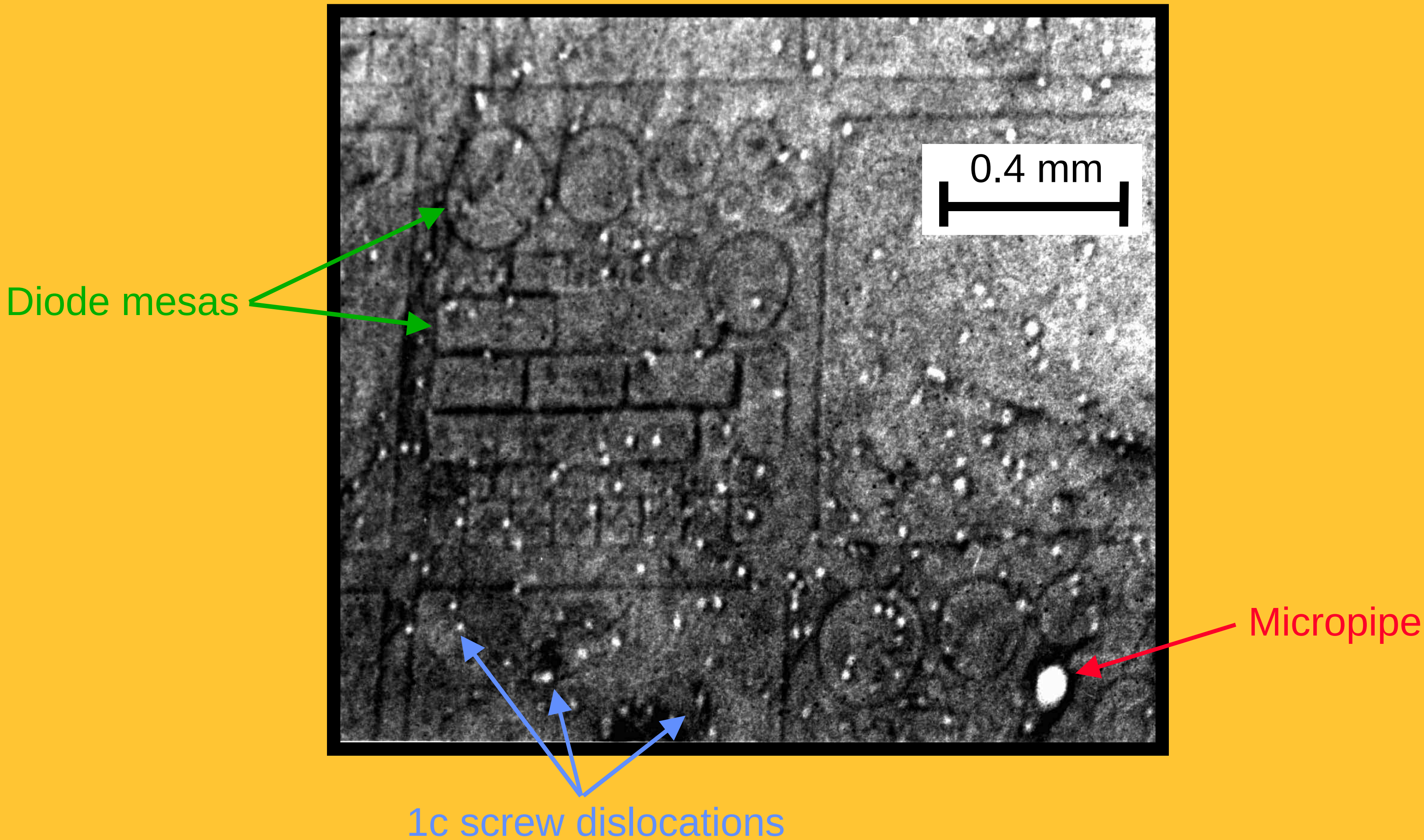
I-V characterize devices with and without defects.

- Emphasis on high-field reverse leakage and breakdown voltage.
- Truest measure of material quality.
- Power device reliability related to breakdown properties.

Remove contacts from devices, optically observe device under bias.

- Use light emission to pinpoint electrical anomalies and failures.
- Probe placed on p^+ contact sufficient for mA current measurements.

X-Ray Topographic Image of 4H-SiC p^+n Diode Wafer Section



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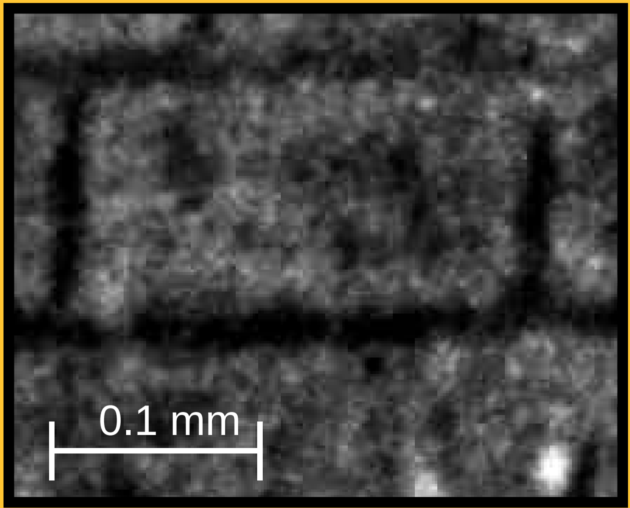
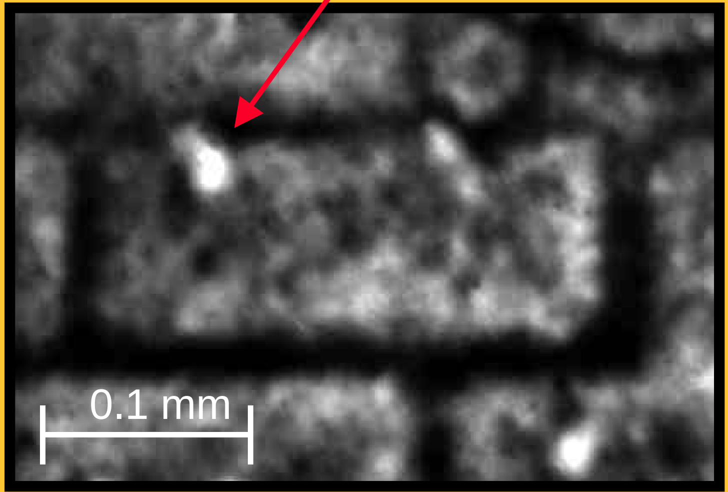
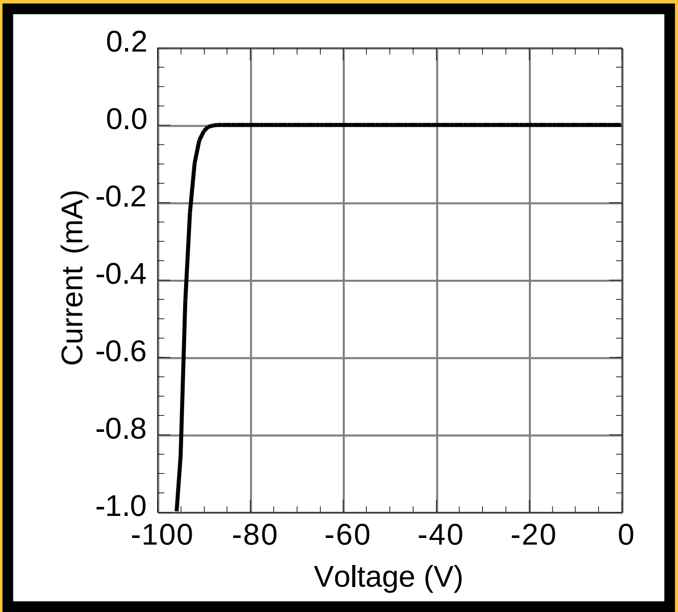
Diode without 1c screw dislocation

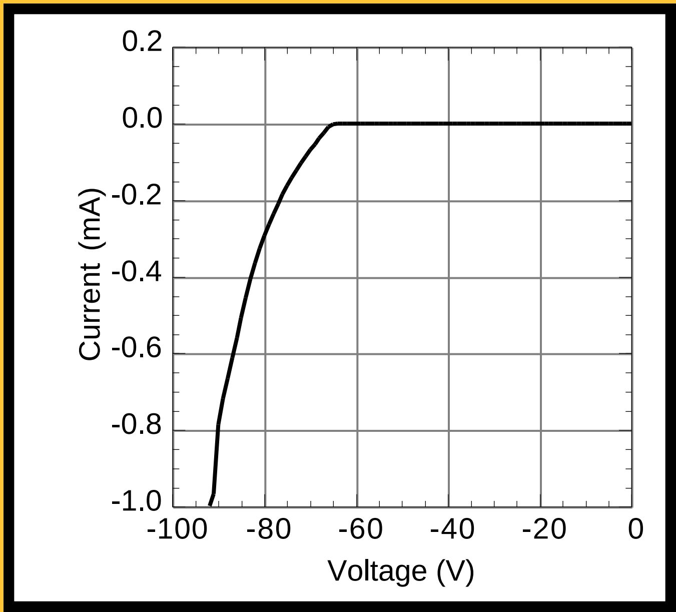


Diode with 1c screw dislocation



X-Ray Topographic Images of Rectangular Diodes on Same Wafer.





Reverse I-V Characteristics (T_A = 300 K)

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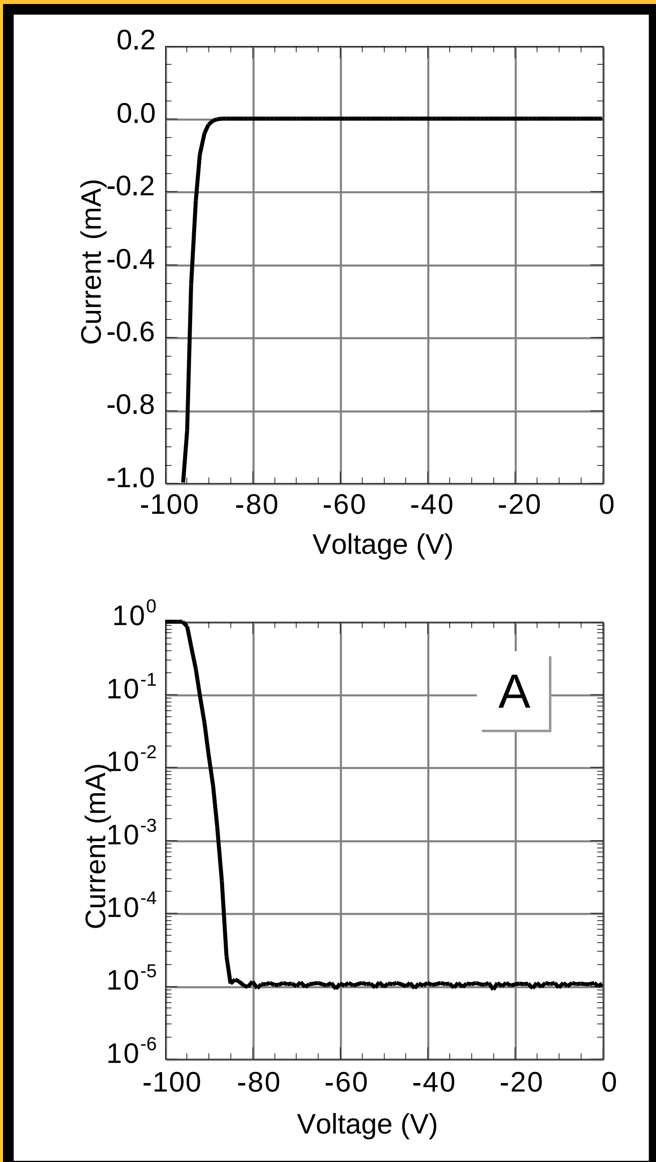
Diode without 1c screw dislocation

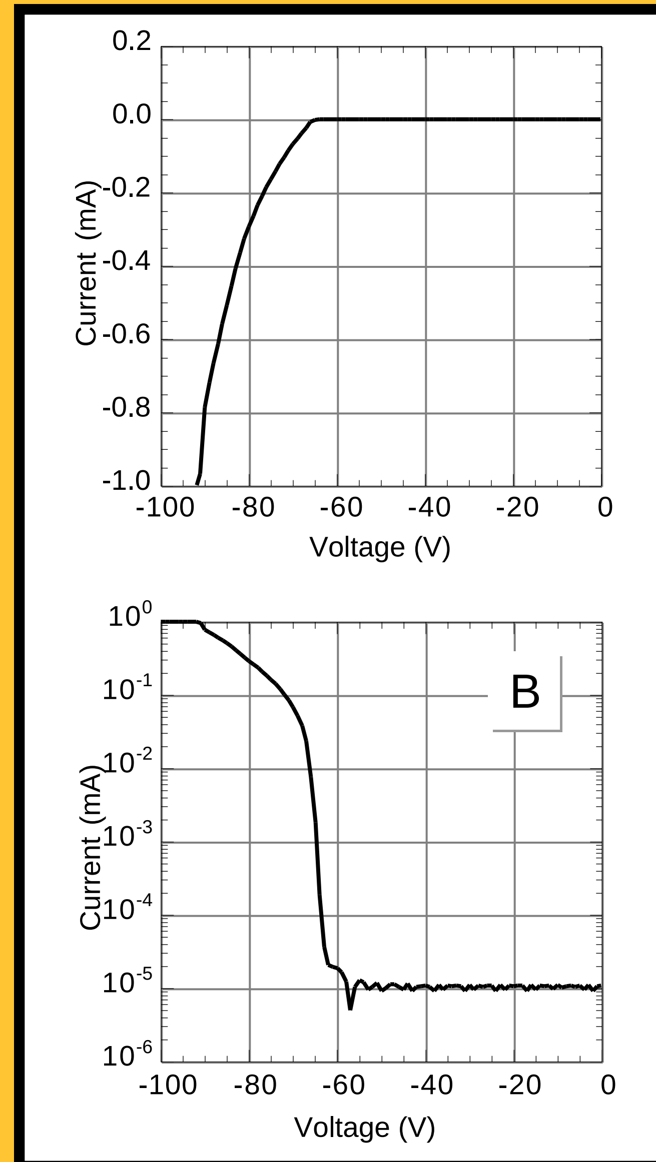


Linear
Reverse I-V
Characteristics

T_A = 300 K

Semi-Logarithmic
Reverse I-V
Characteristics

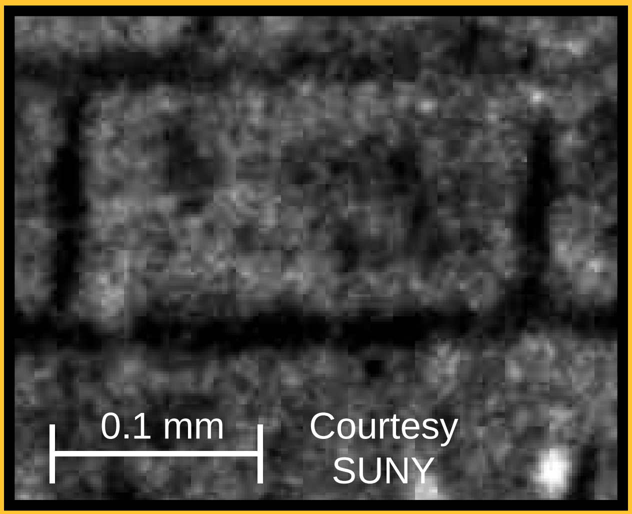
Diode with 1c screw dislocation

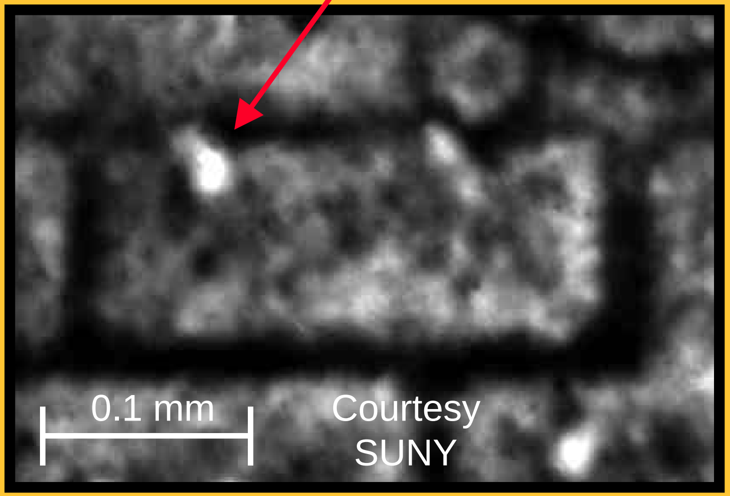


Breakdown Microplasma Corresponds to 1c Screw Dislocation

Diode without 1c screw dislocation

Diode with 1c screw dislocation





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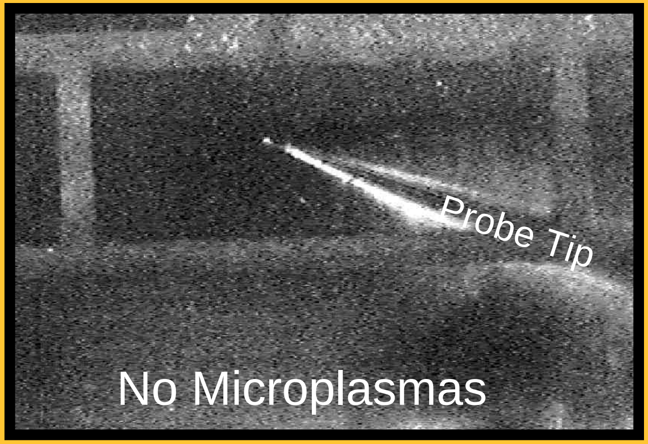
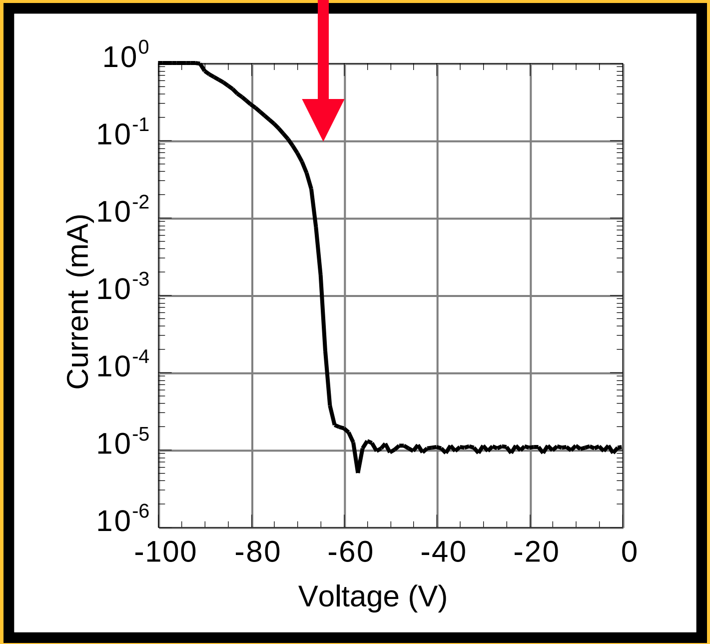


Low-light Optical Micrographs of Breakdown-Bias Luminescence

Microplasma Characteristics

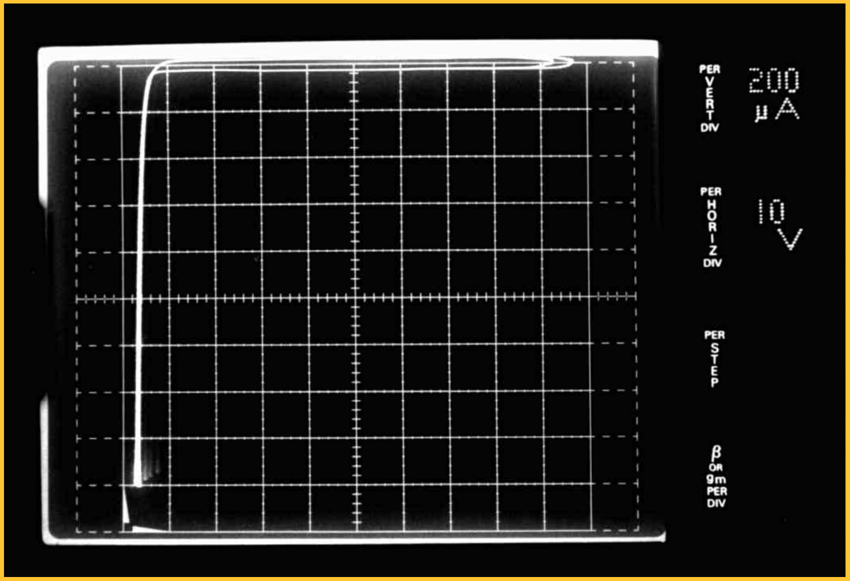
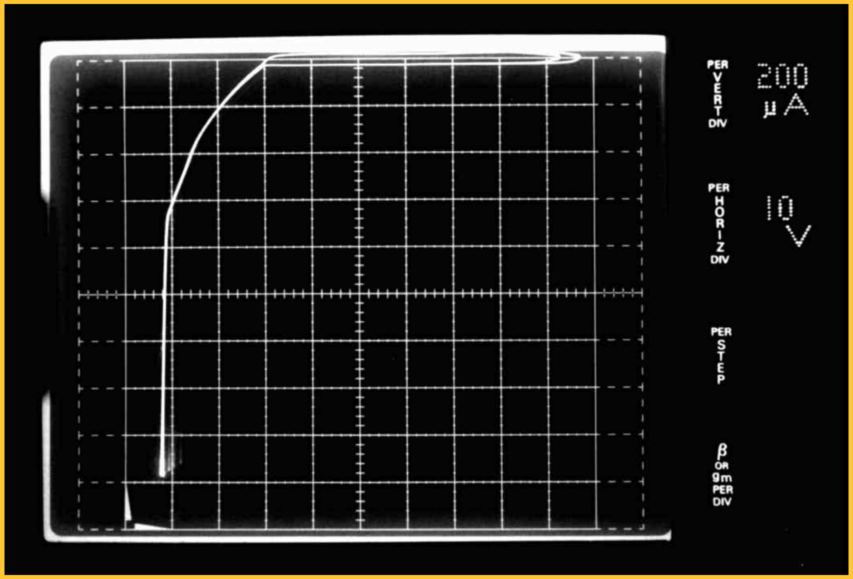
Microplasma turn-on



Low-Light Optical Micrograph of
Breakdown-Bias Luminescence

- •Microplasma turn-on coincides with measured current increase.
- •Microplasma physical size less than 5 µm, located at 1c screw dislocation.
- •All measured current between 65 V and 90 V is flowing at screw dislocation.
- •Microplasma DC power density > 10 kW/cm^2, dissipated in < 0.3% of device area.
- •Non-destructive under small-area contactless measurement conditions.
  - <u>Not representative of actual power device operating conditions.</u>

Curve-Tracer Data

Diode without 1c screw dislocation (100 µm diameter device)	Diode with 1c screw dislocation (100 µm diameter device)
	

Dislocation does not carry all breakdown current as bias increased beyond 92 V.

Devices with 1c screw dislocations exhibit bulk breakdown luminescence when sufficient breakdown bias is applied.

Energy density remains highest at 1c screw dislocation.

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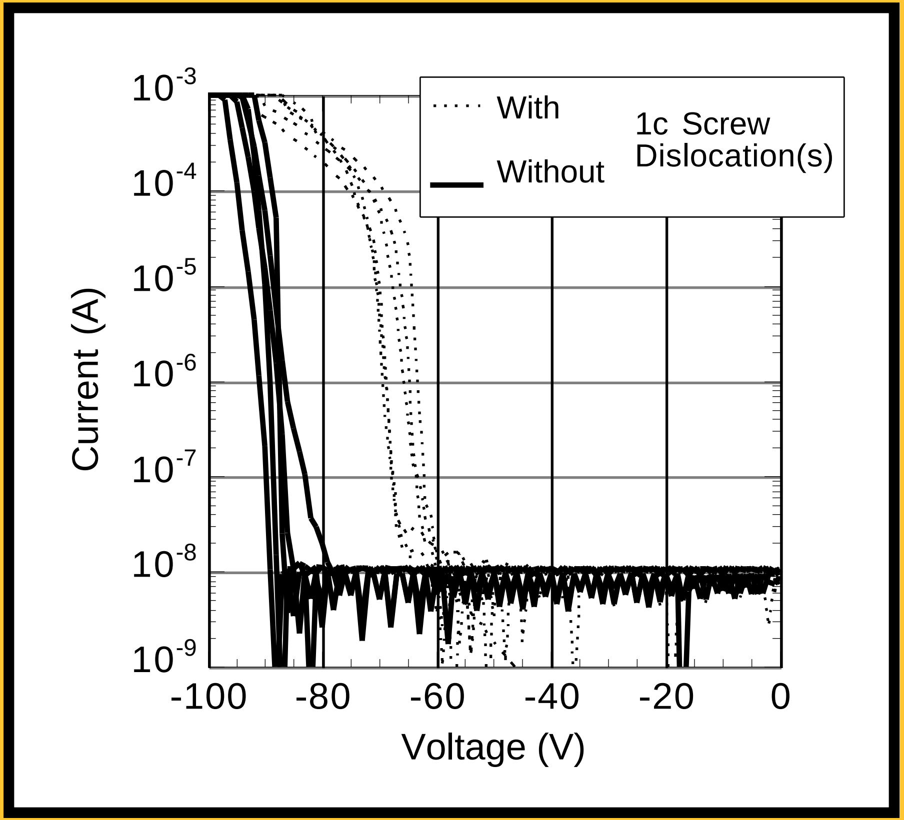
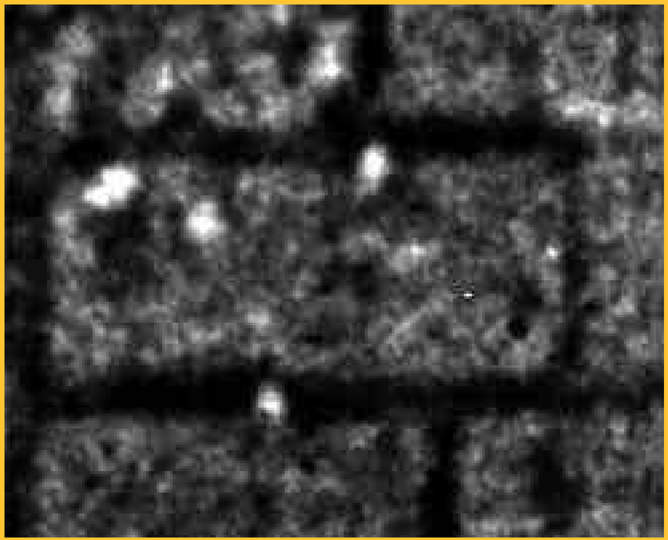
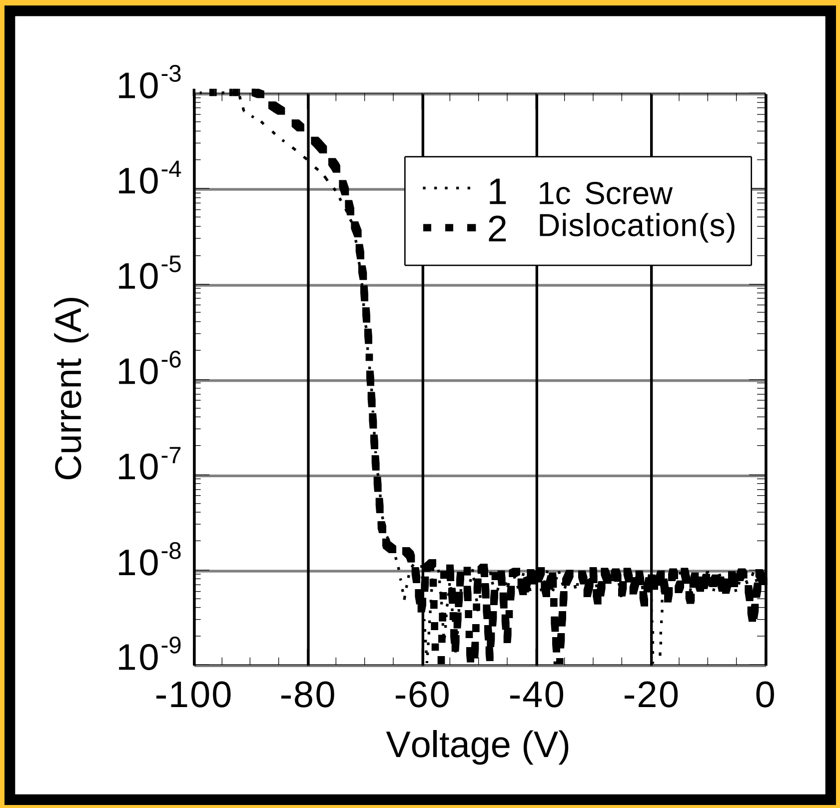
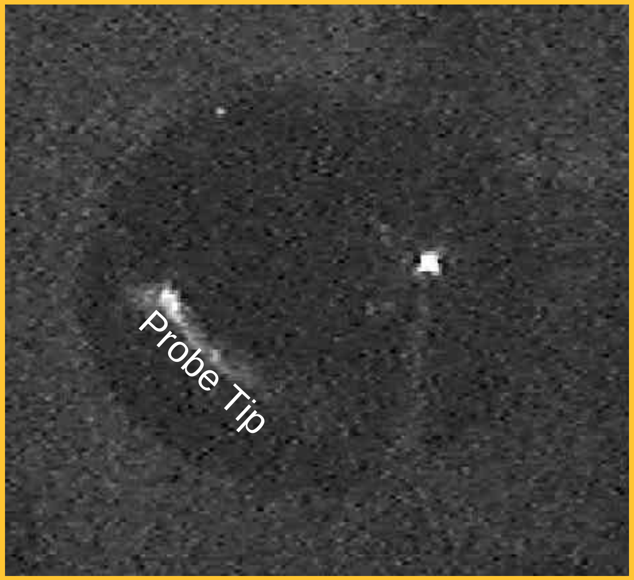
Without exception, every diode that SWBXT identified as containing an elementary screw dislocation exhibited degraded reverse I-V and microplasmic breakdown.

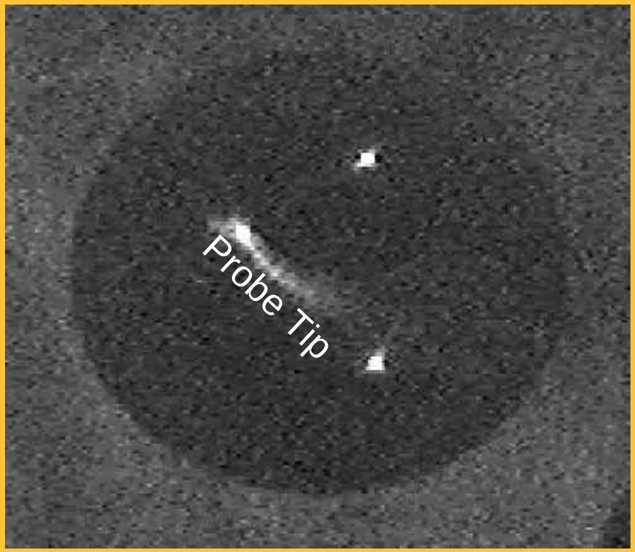




Devices with more screw dislocations (microplasmas) exhibit higher "soft knee" breakdown currents.







Possible Defect-Assisted Breakdown Mechanisms

What is physics behind local decrease in 4H-SiC breakdown voltage in vicinity of elementary screw dislocation?

Avalanche (impact ionization) breakdown or tunneling breakdown?

Local lattice deformation changing local band structure?

- Reduced bandgap?
- Enhanced high-field carrier transport or reduced scattering?

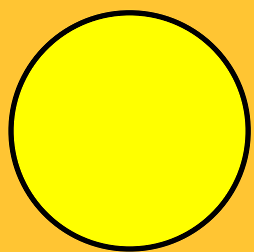
Dangling bonds along screw dislocation?

Enhanced impurity incorporation at screw dislocation?

Further research needed to ascertain defect-assisted breakdown mechanisms.

Breakdown Properties & Power Device Reliability*

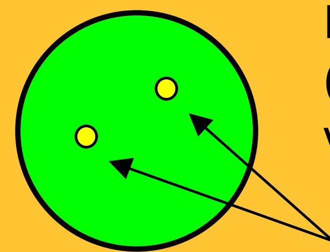
Diode Area



Breakdown current (energy) evenly distributes over the entire device area.

- Positive Temperature Coefficient of Breakdown Voltage Behavior
- Devices withstand very high energy before damage or failure occurs.
- Large Safe Operating Area.
- High immunity to system overvoltage glitches, EMP, lightning, etc.
- Very high reliability power devices.

Diode Area



Breakdown current (energy) localized to very small area(s).

Current Filaments

- Negative Temperature Coefficient of Breakdown Voltage Behavior
- Devices withstand much less energy before damage or failure occurs.
- Reduced Safe Operating Area.
- Lower immunity to system overvoltage glitches, EMP, lightning, etc.
- Compromised power device reliability.

*Paraphrased from Bell Labs EMP Handbook, Expired MIL STD’s 19500 & 461, and other literature sources.

<u>Experimental Observations:</u>

1c screw dislocation densities outnumber micropipes 100-fold in SiC.

1c screw dislocations originate in substrates & propagate into epilayers.

1c screw dislocations degrade high-field behavior of SiC p^+n rectifiers, albeit to a much smaller degree than micropipes.

- 5% to 35% breakdown voltage degradation, softened breakdown knee.
- High energy density current filaments (microplasmas) at 1c dislocations.
- Microplasmas non-destructive as measured.

<u>Conclusion</u>: 1c screw dislocation defects are <u>not totally harmless</u> to the high-field characteristics of SiC power devices.

<u>Unresolved Key Question</u>: To what degree will 1c screw dislocations impact various SiC power device structures? (Major or minor?)

Impact must be <u>quantified</u> in terms of:

- Device ratings & safe operating area.
- Device reliability, immunity to glitches & EMP.

Experimental Limitations:

Testing not representative of actual power-device operating conditions!

This Experiment	Operational Power Devices
•Small-area (< 5 x 10^{-4} cm^2)	•Large-area (> 0.5 cm^2)
•Low-voltage (< 0.2 kV)	•High-voltage (> 1 kV)
•Low-current (< 100 mA)	•High-current (> 100 A)
•No top contact metallization	•Highly ohmic contacts
•High series resistance	•Very low series resistance
•DC testing	•Fast switching (switching stress)
•Limited number of measurements	•Multi-year operation
•Diode - no bipolar amplification	•Thyristors, IGBT’s, etc. = bipolar amplification

Prior experience in silicon high-power teaches that concentrated breakdown currents harm device reliability (degree varies with device structure).

How applicable is silicon experience to silicon carbide?

Key material properties (Debye temperature, thermal conductivity, etc.) are vastly different!

Conclusions

Elementary 1c screw dislocations negatively affect high-field SiC device properties.

Degree of impact unknown - likely to vary with device structure.

Prototype SiC devices should undergo breakdown & fast switching reliability testing, so that accurate reliability models for SiC power devices can be developed.

Continued studies are tentatively planned (depending on funding).